NAVWEPS REPORT 7383

THE PITCH-YAW-ROLL COUPLING PROBLEM OF GUIDED MISSILES AT HIGH ANGLES OF PITCH (U)

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U. S. NAVAL ORDNANCE LABORATORY

WHITE OAK, MARYLAND

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THE PITCH-YAW-ROLL COUPLING PROBLEM OF GUIDED MISSILES AT HIGH ANGLES OF PITCH

Prepared by:

Gerald Corning

ABSTRACT: A study has been made of the pitch-yaw-roll coupling problem to determine

a) how the problem arises,
b) the general effects of this coupling on the flight of missiles, and
c) how the adverse effects of the coupling can be minimized.

The coupling results primarily from the fact that at high angles of attack, the pressure on the windward side of the missile is greater than on the lee side. For equal deflections of the vertical control surfaces, the surface on the windward side will produce a higher force than the one on the lee side, thereby producing a rolling moment as well as a side force. In addition, when the angle of pitch and the angle of roll are not equal to zero, the vortices from the fuselage nose introduce control surface forces in such a manner as to cause a rolling moment, which also affects the coupling.

The general effects of this coupling have been to render some missiles uncontrollable under certain conditions of angle of pitch and Mach number, and other missiles to become merely more difficult to control precisely. These adverse effects may be minimized by proper guidance systems and aerodynamic design.

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The purpose of this investigation is to present how the problem of pitch-yaw-roll coupling arises, what the general effects of this coupling on the flight of missiles are, and how the adverse effects of the coupling can be minimized. This work was carried out under Task Number RUAW 2A001.

W. A. COLEMAN
Captain, USN
Commander

R. KENNETH LOBB
By direction

CONTENTS

ILLUSTRATIONS

THE PITCH-YAW-ROLL COUPLING PROBLEM OF GUIDED MISSILES AT HIGH ANGLES OF PITCH

INTRODUCTION

1. The problem of pitch-yaw-roll coupling occurs because, if the angle of pitch is not equal to 0, the pressures are such that the forces on the control surfaces on the lee side of the body are lower than those on the windward side. It is further complicated when the aerodynamic roll angle is not 0^{o}, by the influence of the nose-induced vortices.

2. The vehicle being discussed is an axisymmetrical body with cruciform tail surfaces with the fins numbered as shown in Figure 1. As shown, fin 1 is above the center line of the body at $\phi = 0$, and it is this position in which the vehicle is launched and which the guidance tries to maintain.

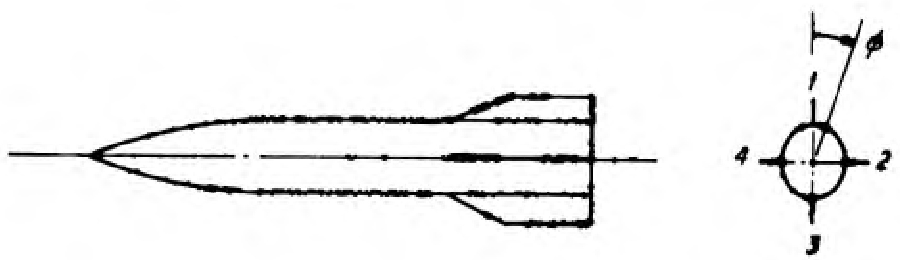

Figure 1 - Vehicle Configuration at $\phi = 0^{o}$

3. In this report note that vertical surfaces and i_v refer to surfaces 1 and 3, while horizontal surfaces and i_h refer to surfaces 2 and 4.

4. To simplify the discussion, the only angles used in this report are θ, ϕ_a, and ϕ_e. (See list of symbols for exact meaning.) This is possible by assuming that the body axis and the free stream always lie in the vertical plane. The aerodynamic forces on the surfaces are varied by rolling the vehicle about the body axis. Under these conditions, $\phi_a = \phi_e$, and θ,

the angle of pitch, is also the complex angle of attack. Although $\phi_e = \phi_a$, ϕ_e will be used when guidance is discussed, and ϕ_a when aerodynamic forces are significant. It should be noted that the assumptions made in no way limit the application of the results, since the forces on the body and surfaces can be realized by other combinations of angles. The planes will be referenced in the following manner:

the plane of θ	the pitch plane (also plane of elevation)
the horizontal plane	the yaw plane (also plane of azimuth)
the plane of α	the plane of fins 1 and 3
the plane of β	the plane of fins 2 and 4

SYMBOLS

θ	the angle of pitch; the angle between the body axis and the free stream in a plane perpendicular to the earth
ϕ_a	the aerodynamic roll angle; the angle between fin 1 and the plane of the free stream and axis of symmetry
ϕ_e	the roll angle, referred to the earth axis, is used for guidance. This is required since trajectories are referred to the earth, and guidance is used for trajectory control
α	the angle of attack; equals $\tan^{-1}(\cos \phi_a \tan \theta)$
β	the angle of sideslip; equals $\tan^{-1}(\sin \phi_a \tan \theta)$
i	fin deflections to introduce pitching and/or yawing moments
δ	deflections of all four fins to introduce a rolling moment
C_l	rolling moment coefficient
C_m	pitching moment coefficient
C_{N_F}	fin normal force coefficient

L_T load on tail

L_F load on fuselage

M Mach number

V_{FS} freestream velocity

W weight

DISCUSSION

THE PITCH-YAW-ROLL COUPLING PROBLEM

5. The problem of pitch-yaw-roll coupling occurs because at $\theta > 0$, the pressures are such that the forces on the control surfaces above the body center line are lower than those on the surfaces below the body center line. It is further complicated when ϕ_a is not 0°, by the influence of the vortices (shed from the nose) on the fins.

6. The results of wind-tunnel tests of individual fins verify these conclusions as shown by the C_{N_F}, the fin normal force coefficient, on the moveable part of the fins at M = 2.35 in Figure 2 (reference 1).

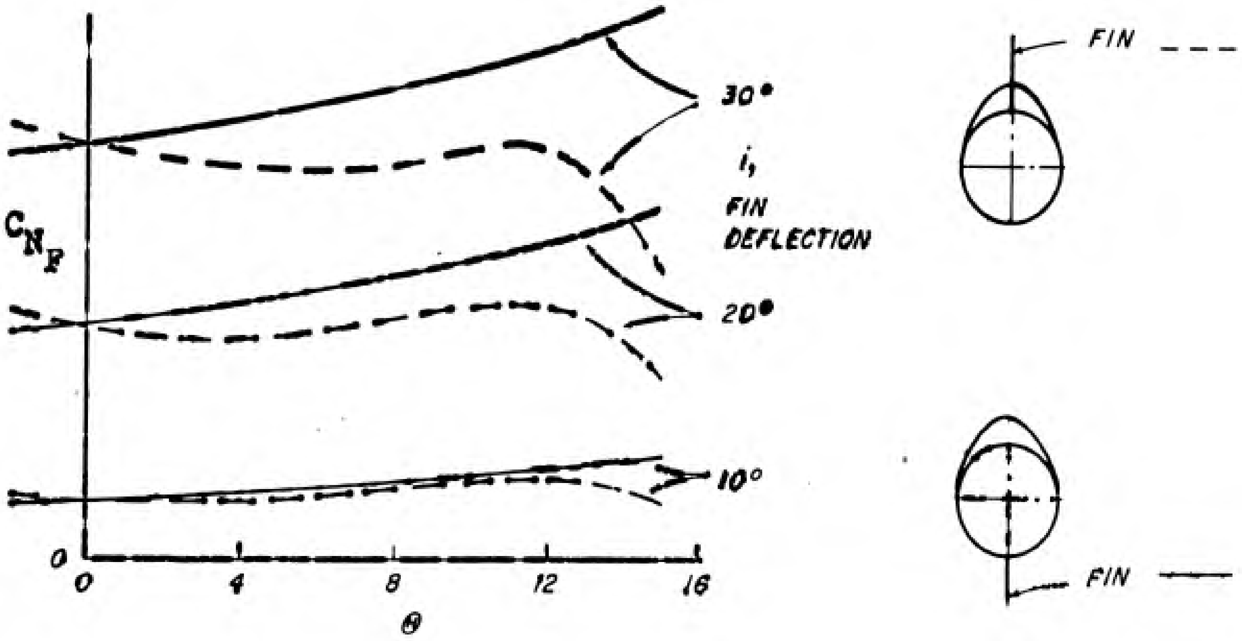

Figure 2 - Individual Fin Loads - Top and Bottom

Note that the C_{N_F} of the lower fin increased as θ increased from 0° to 15°, while the value for the upper fin remained fairly steady from θ = 0 to 12°, and then definitely dropped beyond 12°, particularly at i = 30°.

7. The significance of this phenomenon is that if a correction in azimuth is required so that the vertical fins are deflected equally, not only does a side force and yawing moment result, but also a rolling moment. Thus evolves the pitch-yaw-roll coupling. Conversely, if only a roll correction is desired, equal and opposite deflections of the top and bottom fins will not only result in a rolling moment but also in a side force and a yawing moment.

8. The added complications of the effect of the nose vortices are shown by Figure 3, the results of wind-tunnel tests of a fin at ϕ_a = 22.5° at M = 2.35 (reference 1).

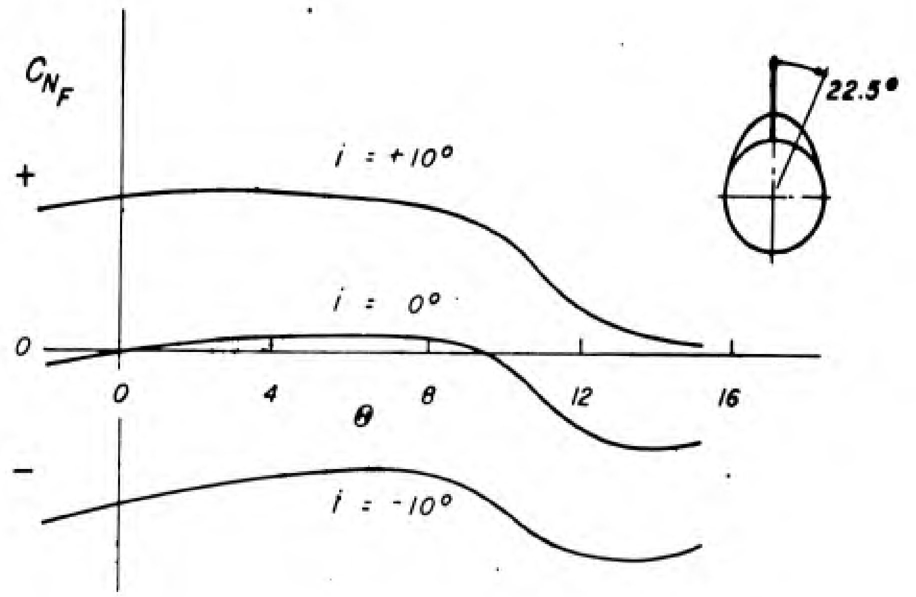

Figure 3 - Individual Fin Load - 22.5°

At $i = +10^{\circ}$, it is noticed that C_{N_F} is almost constant from $\theta = 0^{\circ}$ to 8°. The increase in C_{N_F} expected from an increase in θ is evidently offset by other effects, such as pressure decrease due to shielding by the fuselage and the nose vortices. From these data alone, it is not evident whether this decrease in C_{N_F} is due only to shielding or not. However, a clearer picture is obtained from studying the $i = 0^{\circ}$ curve.

9. For $i = 0^{\circ}$, C_{N_F} increases slightly from $\theta = 0^{\circ}$ to 8°, which might be expected from the increase in θ. However, an increase in θ from 8° to 10° causes C_{N_F} to decrease to 0; and above $\theta = 10^{\circ}$, C_{N_F} reverses sign. Since a decrease in pressure can only decrease the absolute magnitude of C_{N_F}, this reversal of direction of C_{N_F} is evidently due to the effects of the vortices. This can be explained with the aid of Figure 4.

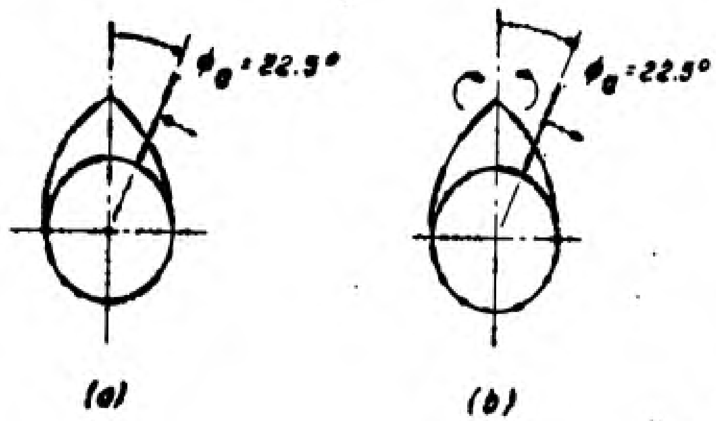

Figure 4 Effect of Nose Vortices on Fin Loads

At $\phi_a = 22.5^\circ$ and $\theta = 14^\circ$, C_{N_F} might be expected to act in the direction shown in Figure 4a, if the effects of nose vortices are neglected. If the nose vortices are in the position relative to the fins as shown in Figure 4b, the C_{N_F} due to the vortices alone would be in the direction indicated. Wind-tunnel tests show that with $\phi_a = 22.5^\circ$ and θ greater than 10°, the total C_{N_F} is in the direction as expected from the vortices alone. It is therefore evident that the C_{N_F} due to the nose vortices must have a greater absolute magnitude than the C_{N_F} due to θ in the pressure field if no vortices existed.

10. From the above data, it is clearly evident that the pitch-yaw-roll coupling problem is a result of the lower pressures acting on the control surfaces on top of the missile than on the bottom due to shielding, and of the strength and position of the nose vortices.

MISSILE DYNAMICS IN THE PITCH-YAW-ROLL COUPLING MODE

11. A missile that has deviated from a given course in the transverse direction receives a signal to deflect its fins so that it will tend to return to the course. If the missile is at $\phi_e = 0^\circ$ and a high θ, the vertical fins only will be deflected. Due to the higher pressure on the lower fin than on the upper, the lower fin will produce the higher normal force and a rolling moment, as shown in Figure 5a.

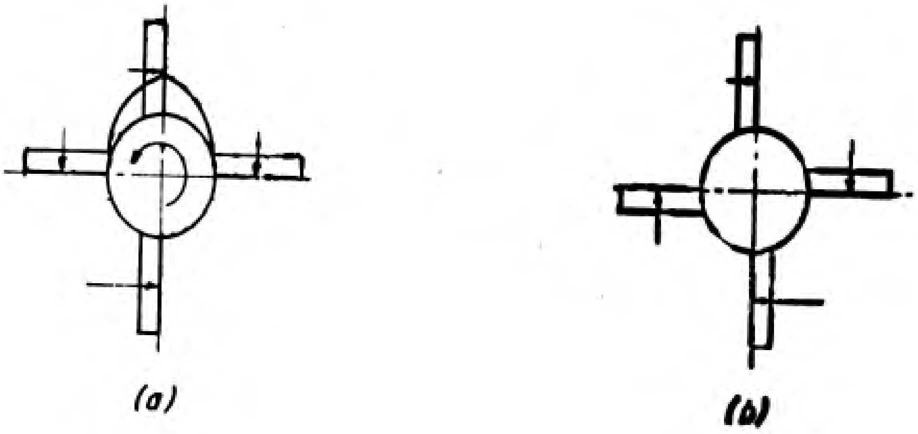

Figure 5 Loads on Moveable Portion of Fins Due to Deflection

This rolling moment will result in a roll displacement and a roll velocity. For a guidance system that tries to maintain $\phi_e = 0$ and either $\phi = 0$, or the rolling velocity about the body axis $= 0$, roll correction is made by additional deflections of all fins, δ, as shown in Figure 5b, with the resulting normal forces. These deflections must be added to the deflections of the vertical fins, i_v, and to the deflections of the horizontal fins, i_h, which were required to maintain a high θ.

12. If i_v and i_h were at their maximum values, any additional δ would decrease one i_v and one i_h and maintain the maximum value of the other. This would mean, that due to this pitch-yaw-roll coupling, the missile could neither maintain its desired θ as required for range, nor correct its direction to return to the desired course, until the roll displacement and roll velocity were corrected. Under certain conditions, this could lead to inaccuracies in final impact.

13. The problem is made more severe if the missile is unstable in roll. A plot of C_l vs ϕ_a for a typical missile with $i_v = i_h = 0$ is shown in Figure 6.

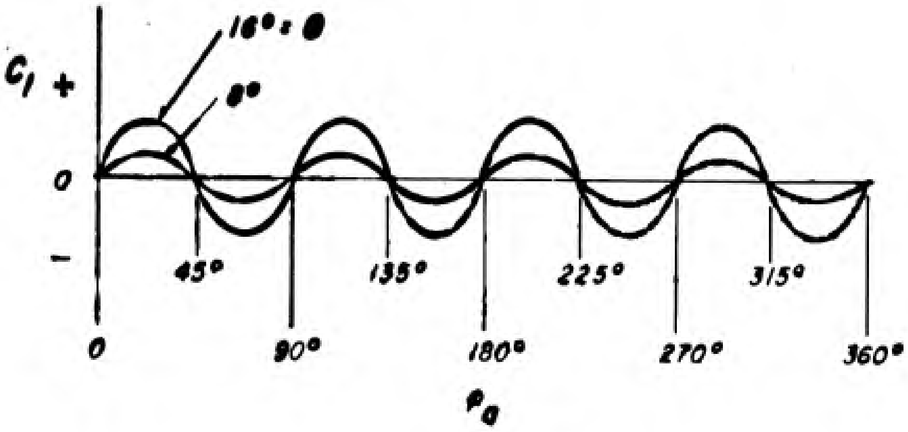

Figure 6 Rolling Moment Coefficient vs ϕ_a

The signs of $dC_l/d\phi$ are such that the missile is unstable at $\phi_a = 0°$, $90°$, etc., and stable at $\phi_a = 45°$, $135°$, etc. These curves change with variations in i.

14. As stated previously, if the missile vertical fins are deflected (to maneuver in azimuth) while at a high θ, a roll is initiated. If the missile were unstable in roll, (that is, when displaced from equilibrium ϕ_a, moments were set up that tended to increase ϕ_a further), not only must the value of δ be such to correct the ϕ_e and $\dot{\phi}_e$ resulting from the C_l due to the i_v, but it must also correct the ϕ_e and $\dot{\phi}_e$ resulting from the C_l due to ϕ_a. The larger resulting δ only causes a further decrease in the net forces on the control surfaces and therefore less control in pitch and yaw.

15. This C_l due to the pitch-yaw-coupling, plus the C_l due to ϕ_a because of the unstable $dC_l/d\phi$ can result in a ϕ_e greater than 45° for some control surfaces and guidance systems. As will be shown later, this value of ϕ_e can be disastrous for certain guidance systems.

EFFECTS OF CROSS-COUPLING

16. The ultimate effect of cross coupling on a particular missile depends on the aerodynamic, structural, and guidance system designs. The aerodynamic design determines the stability of the missile and the effectiveness of the surfaces; both of those characteristics affecting the control of the missile. The structural design is a factor in the ultimate moments of inertia of the vehicle and the response of the missile to an aerodynamic moment is dependent upon its moment of inertia.

17. The design of the guidance system can be critical. Assume that the missile guidance and aerodynamic systems are designed so that the missile is always trying to return to $\phi_e = 0°$ as shown in Figure 1, that the deflection of fins 1 and 3 are always used for a yaw maneuver, and that fins 2 and 4 are always used for a pitch manuever. It is obvious that if the vehicle is rolled 90° and a yaw maneuver is called for by deflecting fins 1 and 3, a pitch maneuver will result. This condition results in a situation where the requirement for a yaw correction results in pitch, and vice versa. A completely uncontrollable missile is the result. Control begins to break down at $\phi_e = 45°$ with this type of guidance system.

18. This problem of reversal of control can be eliminated by introducing a roll resolver into the guidance system. If a correction in pitch is called for (for instance requiring $i_h = 30^o$ when $\phi_e = 0$), this input is routed through the resolver which knows the instantaneous ϕ_e. The resolver then determines that fins 2 and 4 must be deflected $30^o \cos \phi_e$, and fins 1 and 3 deflected $30^o \sin \phi_e$. For yaw control of course, a similar system is used with the sine and cosine functions reversed. In this manner, the moveable surfaces are deflected so that the desired maneuver always results, even if $\phi_e = 90^o$.

MEANS OF MODIFYING THE CROSS-COUPLING EFFECTS

19. Although a resolver in the guidance system does eliminate the possibility of introducing moments in the wrong plane in response to an error signal, it does not entirely eliminate the problems associated with cross coupling.

20. A missile might require a maximum horizontal fin deflection near the end of its flight to achieve the θ required for the desired range. If at the same time, a yaw maneuver is called for, so that the vertical fins must be deflected, a rolling moment results. To correct for the subsequent ϕ_e and rolling velocity, all the surfaces are deflected by some value of δ. Since the horizontal fins are already at their maximum deflection, one fin will stay fixed while the other is deflected, resulting in a reduction of the effectiveness of the surface. In fact, under some conditions, it is possible that the fin could move to the maximum deflection in the opposite direction to its initial position. In this manner, the θ of the missile can be reduced and the range of the missile decreased.

21. Similarly, if a yaw maneuver is desired that requires a maximum deflection of the vertical control surfaces, the resulting δ of all the surfaces to correct the rolling moment due to shielding of the upper surface reduces, or reverses, the deflection of one vertical control surface. In this manner, the desired yaw maneuver is not accomplished, and an inaccuracy results.

Roll Stability

22. In this discussion, it is evident that the magnitude of the δ required to correct for ϕ_e and the rolling velocity

resulting from shielding plays a part in determining the ultimate accuracy attainable by the missile system. This δ will be affected by the roll stability of the missile. Again, the vertical fins are deflected and a rolling moment results. If the missile is aerodynamically stable in roll, a displacement in roll will result in a C_l to oppose the displacement. Therefore, for a given time lag, the missile will not roll to as high a value of ϕ_e or rolling velocity for a given i_v, and a smaller value of δ will be called for to correct ϕ_e and to return the rolling velocity to zero. Inversely, a missile unstable in roll will require a larger δ. It is therefore important to investigate what factors affect roll stability.

23. For a missile that derives its lift only from the fuselage and tail surfaces, at a $+\theta$ an upload is required on the tail for equilibrium, as shown in Figure 7.

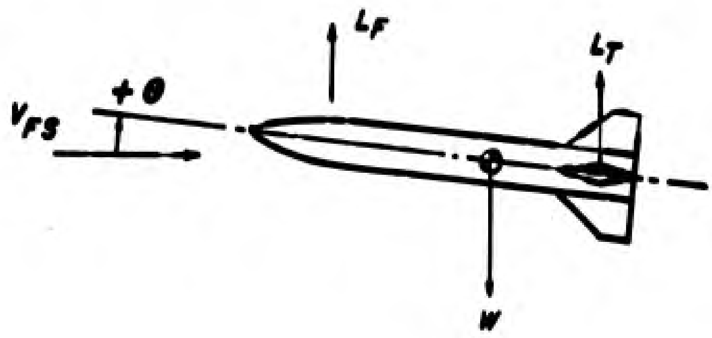

Figure 7 - Equilibrium Forces

If the missile is rolled to some ϕ_a while at a high θ, the forces upon all four control surfaces would be as shown in Figure 8, if the effect of nose vortices are neglected.

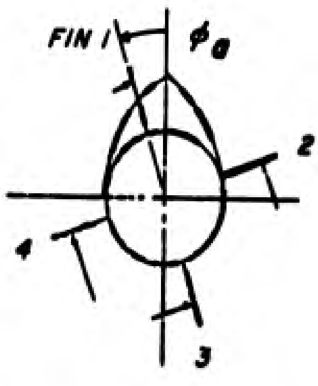

Figure 8 - Fin Forces with $\phi_a = 0°$

24. Due to shielding, $(C_{N_F})_3$ is greater than $(C_{N_F})_1$, and $(C_{N_F})_4$ is greater than $(C_{N_F})_2$. The resulting rolling moment due to forces on fins 1 and 3 is destabilizing (tends to increase ϕ_a) while the rolling moment due to forces on fins 2 and 4 is stabilizing. Whether the missile is stable or not depends on the relative magnitudes of the stabilizing and destabilizing moments. The magnitude of the stabilizing moment due to fins 2 and 4 depends upon the magnitude of the original forces on these surfaces. For a given static margin in longitudinal stability, the missile with the larger horizontal tails will have the c.g. further aft. However, to maintain equilibrium ($C_m = 0$) a larger upload is required on the tail for the vehicle with the c.g. further aft. This larger load tends to increase the roll stability caused by the horizontal surfaces. However, for a cruciform design, the vertical surfaces must also be enlarged if the horizontal surfaces are, thereby increasing the loads on the vertical surfaces, and thereby increasing the degree of instability caused by them.

25. To increase the roll stability it would therefore be necessary to increase the stability of the horizontal surfaces more than the instability of the vertical surfaces, while maintaining the same static margin and the same planforms of all surfaces.

26. Whether it is desirable or not to increase roll stability depends on the attitude that the guidance system is trying to maintain. If the system is designed to try to maintain a roll attitude in which the vehicle is stable (and it is likely that the vehicle will be in the roll attitudes where roll stability results), it is then desirable to make the missile as stable in roll as is feasible. However, for the missile that tries to maintain a roll attitude in which the vehicle is unstable in roll at high θ's (and there are missiles that do), increasing the stability of the vehicle at certain roll angles only increases the instability in the roll angle that the vehicle is trying to maintain. Therefore, for these types of missiles, it would probably be desirable to obtain neutral stability throughout the ϕ range if possible.

The Effect of Nose Vortices

27. As shown previously, the nose vortices can have a significant effect on the loads of the control surfaces, and therefore, on the roll stability characteristics. The exact effect depends upon the strength of the vortices and its

location relative to the control surfaces. These in turn depend upon the shape of the nose, the distance from the nose to the control surface, the planform characteristics of the surface, and the conditions of angle of attack, angle of roll, and velocity.

28. Whether it is feasible, or even desirable, to modify the design of a particular vehicle to influence the effect of the nose vortices on roll stability, would require an intensive study. There is an open field for a general investigation of the effect of the nose vortices on roll stability.

Effect of Nominal Roll Equilibrium Position

29. Figure 6 shows a typical plot of C_l vs ϕ_a for a missile for various values of θ with $i = 0$, and indicates that C_l crosses 0 at eight different values of ϕ. Due to shielding and various values of i, the C_l vs ϕ curve can change drastically. However, it is evident that the vehicle cannot be stable or unstable throughout a 360° range of ϕ_a, but must either alternate, or be neutrally stable throughout.

30. Consider a vehicle with characteristics as shown in Figure 6, i.e., the maximum roll instability at $\phi_a = 0^{\circ}$, 90°, etc., and the maximum roll stability at $\phi_a = 45^{\circ}$, 135°, etc. For the best pitch-yaw-roll characteristics, it would appear that the guidance system should be designed so that the vehicle is always tending to return to the position equivalent to $\phi_a = 45^{\circ}$, and not 0°. With this design, the vehicle will tend to be stable in roll a greater period of time. However, other factors, such as the added complexity of the guidance and control systems, must be considered in the final decision.

Differential Fin Deflections

31. The pitch-yaw-roll problem arises primarily from the fact that a deflection of the vertical fins which is initiated to introduce a yawing moment, also results in a rolling moment due to unequal loads on top and bottom fins. The sequence of events is as follows:

a) the top and bottom fins are deflected in equal amounts, with the resulting rolling moment as well as yawing moment, and

b) the vehicle rolls and all four fins are deflected to correct this rolling displacement and rolling velocity.

Therefore, the vertical fins (as well as the horizontal fins) have different deflections.

32. It has been suggested by E. Marley of The Johns Hopkins University Applied Physics Laboratory, that to obtain a yawing moment the vertical fins be deflected differentially so that the zero roll results, thereby reducing the pitch-yaw-roll problem. It is reported that by this method some improvement could be obtained, although it does complicate the guidance system. The complication arises from the fact that the differential fin deflections required for zero rolling moment depend upon the instantaneous values of V, θ, i_v, i_h, δ, ϕ_a, and ϕ_e.

CONCLUSIONS

33. Although missiles have been launched and guided satisfactorily to their targets by guidance systems without resolvers, it appears that a resolver in the guidance system eliminates the possibility of complete uncontrollability, and reduces the effect of the pitch-yaw-roll problem to one of decreasing accuracy.

34. Since pitch-yaw-roll coupling is severe at high angles of pitch, any means of reducing the maximum angles of pitch necessary will tend to alleviate the coupling problem. An obvious method of accomplishing this is the introduction of lifting surfaces near the c.g.

35. The longer period of time that the vehicle flies when it is stable in roll, the greater will be the attainable accuracy with any guidance system. To accomplish this end, the arbitrary equilibrium ϕ_a should be one at which the vehicle is stable in roll. The design of the control surfaces as to size, planform characteristics, and location should be influenced by its effect on roll stability.

36. The use of control surfaces with differential movements to produce yawing moments without introducing rolling moments should be investigated.

37. The effect of the nose vortices on the control surface loads should be investigated. The study should include the effects of nose shape, control surface planform characteristics and nose-to-surface distances on the nose vortices effect.

38. Although it has not been mentioned before, it is obvious that larger control surfaces and a more sophisticated guidance system will most likely increase the likelihood of hitting a given target with most any vehicle. The larger control surfaces will require smaller i's for control, and thereby be less likely to reach the stops due to superimposed δ's. The guidance system with faster responses will be more effective in control.

39. Lastly, it appears that for a vehicle with a resolver in the guidance system, the pitch-yaw-roll problem is no longer one of controllability versus complete uncontrollability, but one of accuracy versus cost. The methods suggested to alleviate the pitch-yaw-roll coupling problem (thereby increasing the potential accuracy) would in some way increase cost, either by increased weight or by greater complexity.

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A study has been made of the pitch-yaw-roll coupling problem to determine
a) how the problem arises,
b) the general effects of this coupling on the flight of missiles, and
c) how the adverse effects of the coupling can be minimized.

1. Missiles - Aerodynamics
2. Missiles - Pitching
3. Missiles - Yaw
4. Missiles - Roll
I. Title
II. Corning, Gerald
III. Project

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